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An instrumentation engineer's review on smart grid: Critical applications and parameters

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ABSTRACT

Conventional electrical grid is transforming into smart grid—an evolutionary solution to satisfy rapidly emerging and vibrantly changing requirements of utilities and customers by intelligently leveraging telemetry concepts of instrumentation and control engineering in form of communication technology network infrastructure. The paper presents analogy of 'smart grid' to 'industrial process' and 'communication technology infrastructure' to 'instrumentation telemetry'. Automated Metering Infrastructure (AMI), monitoring and automation of substations, power network monitoring, Home Automation Network (HAN), Demand Response (DR) and integration of solar PV—have been identified as 'Critical Applications' and Reliability, Scalability, Interoperability, Congestion, Energy Efficiency, Latency and

Abbreviations: ABDP, Accumulated Bandwidth Distance Product; AEPS, Area Electric Power System; AIHC, Average Interruption Hours of Customer; AM, Amplitude Modulation; AMI, Advanced Metering Infrastructure; AMR, Automated Meter Reading; ARQ, Automatic Repeat Query or Automatic Repeat reQuest; CIM, Common Information Model; CM, Condition Monitoring or Congestion Management; CoHEM, Coordinated Home Energy Management; CoSMoNet, Cost-aware Smart Microgrid Network; CSMA/CA, Carrier Sense Multiple Access with Collision Avoidance; CT, Current Transformer; DAU, Data Aggregator Unit; DBMS, DataBase Management System; DBPC, DataBase Processing Center; DCU, Data Concentrator Unit; DDU, Dharmsinh Desai University; DER, Distributed Energy Resource; DES, Distributed Energy Storage or Distributed Energy Systems; DRES, Distributed Renewable Energy Sources; DG, Director General or Distributed Generation or Decentralized Generation; DG&S, Distributed Generation and Storage; DoS, Denial-of-Service; DR, Demand Response; DREGs, Distributed Renewable Energy Generators; DRX, Delay-aware cross layer; DSEM, Demand Side Energy Management; DSM, Demand Side Management; DSP, Digital Signal Processor; DT, Delaunay Triangulation; EMS, Energy Management System; EMU, Energy Management Unit; EPS, Electric Power System; EV, Electric Vehicles; FDR, Frequency Disturbance Recorder; FDRX, Fair and Delay-aware cross layer; FLC, Fuzzy Logic Control; FM, Frequency Modulation; FNET, Frequency monitoring NETwork; FRA, Frequency Response Analysis; FRL, Find Reliable Link; GERMI, Gujarat Energy Research and Management Institute; GFN, Ground Fault Neutralizer; GIS, Geographic Information System; GPRS, General Packet Radio Service; GPS, Global Positioning System; GWAC, GridWise®® Architecture Council; HAN, Home Automation Network or Home Area Network; HASG, High Assurance Smart Grid; HEMS, Home Energy Management System; HES, Head End System; HMI, Human Machine Interface; HWMP, Hybrid Wireless Mesh Protocol; IC, Instrumentation and Control or Integrated Circuit; ICMP, Internet Control Message Protocol; ICT, Information and Communication Technology; IEC, International Electrotechnical Commission; IED, Intelligent Electronic Device; IEEE, Institute of Electrical and Electronics Engineers; IET, Institution of Engineering and Technology; iHEM, in-Home Energy Management; ILP, Integer Linear Programming; IoT or IOT, Internet of Things; IP, Internet Protocol; ISA, International Society of Automation; ISO, Independent System Operators or International Standards Organization; IT, Information Technology; ITP, Interoperability Test Platform; ITU, International Telecommunication Union; LAN, Local Area Network; LCIM, Levels of Conceptual Interoperability Model; LOLP, Loss Of Load Probability; M2M, Machine to Machine; MAC, Medium Access Control; MAS, Multi-Agent System; MATLAB, MATrix LABoratory; MCEM, Monte Carlo Expectation Maximization; MCS, Monte Carlo Simulation; MDMS, Meter Data Management System; MPC, Model Predictive Control; MTBF, Mean Time Between Failure; MTTR, Mean Time To Repair; MV/LV, Medium Voltage/Low Voltage; NAN, Neighborhood Area Network; NCAP, Network Capable Application Processor; NCC, Network Control Center; NIST, National Institute of Standards and Technology; NN, Neural Network; ODSRAS, On-line Distribution System Risk Assessment System; OLTC, On-Load Tap-Changer; OREM, Optimization-based Residential Energy Management; PD, Partial Discharge (PDA: Partial Discharge Analysis); PERSON, PERvasive Service-Oriented Networks; PDPU, Pandit Deendayal Petroleum University; PHEV, Plug-in Hybrid Electric Vehicle; PHIL, Power-Hardware-In the-Loop; PHY, PHYsical; PKI, Public Key Infrastructure; PLC, Power Line Communication; PLCC, Power Line Carrier Communication; PMU, Phasor Measurement Unit; PPCOM, PLC Power Controlled Outlet Module; PPS, Photovoltaic Power System; PV, Photo Voltaic; QoS, Quality of Service; RBD, Reliability Block Diagram; RBTS, Roy Billinton Test System; RDAU, Remote Data Acquisition Unit; RMCPS, Remote Monitoring and Controlling Power Socket; RSS, Remote Sensor System; RTO, Regional Transmission Organization; RTP, Real Time Pricing; RTU, Remote Terminal Unit; SAS, Single Agent System; SCADA, Supervisory Control And Data Acquisition; SCSN, Spectrum-aware Cognitive Sensor Network; SCUC, Security Constraint Unit Commitment; SDG, Smart Distribution Grid; SEDAX, SEcure Data-centric Application eXtensible; SEP, Smart Energy Profile; SG, Smart Grid; SGIMM, Smart Grid Interoperability Maturity Model; SHEMS, Smart Home Energy Management System; SMGN, Smart Micro Grid Network; SMS, Short Message Service; SoS, System of Systems; SPS, Special Protection System; SSTP, Scalable and Secure Transport Protocol; TDMA, Time Division Multiple Access; TCP, Transmission Control Protocol; ToU, Time of Use; TVWS, Tele Vision White Space; UGVCL, Uttar Gujarat Vij Company Limited; UK, United Kingdom; USA (or US), United States of America; UTC, Coordinated Universal Time; VAR, Volt-Ampere Reactive; V2G, Vehicle-to-Grid; WAMS, Wide-Area Measurement System; WAN, Wide Area Network; WCRN, Wireless Cognitive Radio Network; WDM, Wavelength Division Multiplexing; WECC, Western Electricity Coordinating Counci; Wi-Fi or WiFi, Wireless Fidelity; WiMAX, Worldwide interoperability for Microwave Access; WLAN, Wireless Local Area Network; WMN, Wireless Mesh Network; WSN, Wireless Sensor Network; WSHAN, Wireless Sensor Home Area Network; WTIM, Wireless Transducer Interface Module; XMPP, eXtensible Messaging and Presence Protocol

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Communication technology
Instrumentation and control
Measurement and monitoring
Telemetry
Automation

Security – have been identified as 'Critical Parameters'. Review of recent works has been presented for each segment.

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Contents

1. Introduction [1–6]

The smart grid (SG) has started attracting attention of global research community and demonstrating rapid growth potential. SG is transformation of the legacy stand-alone unidirectional non-intelligent electric grid into automatic-intelligent-adaptive system of systems for bidirectional exchange of electric power and information. Reliability of critical power infrastructures has been the area of major focus today, wherein smart grids are expected to play game changing role. SG, the modernization of conventional power grid using technological advancements, is digital automation of electric power system from power generation to customer appliance for improvements of quality, reliability, efficiency and environmental friendliness. SG facilitates for active participation of consumers with timely access and control to their energy usage. Consumers can bid their energy resources at the electric market. SG supports real-time power quality monitoring and active diagnostics to respond power quality deficiencies and reduces loss to customers due to insufficient quality of power. SG possesses the capability to anticipate and respond to system disturbances by continuous self assessment to take corrective action.

Constantly changing customer choices-behavior, increased integration of renewables, varieties of DR programs, etc. all are likely to increase the fluctuations in the ratio of produced and consumed power. Hence, utilities must make strong efforts to deal with the increasing volatility and vibrancy in classification, affordability, feasibility and final choices of power production, demand, distribution and consumption. Important features, such as Real Time Pricing (RTP), require intensive monitoring of the consumers' power consumption patterns along with close real-time asset monitoring and timely provision of control actions. This necessitates data prioritization and delay-responsiveness using communication links with sufficient reliability, data rates and latency.

Communication is expected to play quite significant role in overall SG evolution by facilitating services such as self-healing, real-time demand response and efficient use of energy. Due to the large number, distributed and intermittent nature of energy resources (e.g. wind and solar plants), SG will rely heavily on communication for super-fast balance between demand and supply of electricity. A quick and accurate match between electricity supply and demand has financial and technical benefits. This helps avoid running extra costly plants (e.g. gas turbines) on peak hours and enhances power grid stability. In order to realize the SG vision, it is necessary to have guaranteed QoS for the reliable communication and networking technology used in various SG subsystems, ranging from power generation, transmission, distribution, to the customer service applications. Rapidly growing Communication Technologies have also been proved as vital development forces deciding present and future evolutionary designs of smart grids. Recent developments in software-networking technologies and cost-effective hardware availability are supporting increasing penetration of SGs not only at large scale installations, but also at private-residential applications as well in forms of Microgrids via islanding techniques. Overall, Smart Grid promises good opportunities for future work in research and novel application developments for the growing residential as well as industrial-commercial domains in the interest of the nation.

1.1. *The smart grid: Architecture, applications and services [1–5]*

IEEE P2030 defines the Smart Grid as the power, communications, and information technologies for an improved electric power infrastructure serving loads while providing for an ongoing evolution of end-use applications. IEEE P2030 also defines *Smart Grid as "System of Systems"* (*SoS*) as the smart grid is a complex system made up of interrelated systems.

Table 1.1 below presents interesting comparison between conventional grid and smart grid. The SG results into special features such as self-moniotring and self-healing, adaptive and islanding, pervasive control and most importantly, provision of more choices for consumers; all of these features are possible on account of bidirectional flow of energy and information.

Fig. 1.1 below depicts the NIST conceptual model for SG. According to the model, bidirectional flow of power and communication takes place between bulk generation, transmission, distribution and customer. Markets and Operations controls all of them via bidirectional secure information flow.

According NIST, the following are anticipated benefits and requirements of SG:

(i) Improving power reliability and quality.
(ii) Optimizing facility utilization and averting construction of back-up (peak load) power plants.
(iii) Enhancing capacity and efficiency of existing electric power networks.
(iv) Improving resilience to disruption.
(v) Enabling predictive maintenance and self-healing responses to system disturbances

Table 1.1
Comparison: conventional v/s smart grid [1].

Conventional grid	Smart grid
Electromechanical	Digital
One-way communication	Two-way communication
Centralized generation	Distributed generation
Few sensors	Sensors throughout
Manual monitoring	Self-monitoring
Manual restoration	Self-healing
Failures and blackouts	Adaptive and islanding
Limited control	Pervasive control
Few customer choices	Many customer choices

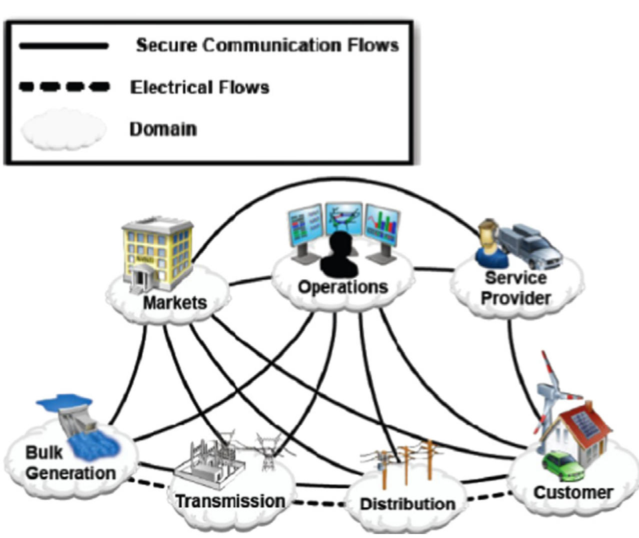

Fig. 1.1. The NIST conceptual model for SG [1].

(vi) Facilitating expanded deployment of renewable energy sources.
(vii) Accomodating distributed power sources.
(viii) Automating maintenance and operation.
(ix) Reducing greenhouse gas emissions by enabling electric vehicles and new power sources.
(x) Reducing oil consumption by reducing need for inefficient generation during peak usage periods.
(xi) Presenting opportunities to improve grid security
(xii) Enabling transition to plug-in electric vehicles and new energy storage options.
(xiii) Increasing consumer choice.
(xiv) Enabling new products, services and markets.

Fig. 1.2 below presents the SG architecture with associated systems and sub-systems. Overall SG architecture could be split into three major systems: smart infrastructure system, smart management system and smart protection system.

1.1.1. *Smart infrastructure system*

The smart infrastructure system is the energy, information, and communication infrastructure underlying of the SG that supports—

(i) Advanced electricity generation, delivery, and consumption.
(ii) Advanced information metering, monitoring, and management.
(iii) Advanced communication technologies.

The smart infrastructure system has been further split into three subsystems: smart energy subsystem, smart information subsystem, and smart communication subsystem.

1.1.2. *Smart management system*

The smart management system is the subsystem in SG that provides advanced management and control services.

The smart management system has also been split further into two subsystems: management objectives, and management methods and tools.

1.1.3. *Smart protection system*

The smart protection system is the subsystem in SG that provides advanced grid reliability analysis, failure protection, and security and privacy protection services.

The smart protection system has also been split further into two subsystems: system reliability and failure protection; and security and privacy.

Table 1.2 below presents the list of SG applications and their major services provided. For serving our objective of study of SG communication technology and its envisaged role of instrumentation telemetry by us, we have covered results of literature survey for the first six core applications.

1.2. *Analogy: Smart grid communication system analogous to instrumentation telemetry system [6]*

Conceptually, the term *telemetry* has been derived from Greek roots: *tele* = remote, and *metron* = measure. Instrumentation telemetry is bidirectional, high performance, reliable, automated, intelligent communication system by which measurements, control signals and other relevant data could be acquired and acquisitioned from remote or inaccessible points and transmitted to centralized control room instruments to serve purposes such as real-time monitoring, recording, control, and/or alarm annunciation, etc.

For example, in most typical application of SG, AMI, the smart meter consists of a communication module or interface (embedded in the meter or externally-remotely connected) which, at specific sampling time periods, establishes communication and fetches the

Fig. 1.2. The smart grid architecture with associated systems and sub-systems [1].

sampled reading data to the DCU. Finally, DCU passes on thus aggregated data received from different meters-modems to HES of utility company using a secure proxy server like an M2M system for further processing in systems such as MDMS. Using this real-time information, the utility company can decide about allocation of resources and tariff/payment calculations based on the difference between inflow and outflow of energy at any given point of time.

A fundamental requirement for an effective remote monitoring application has been availability of a reliable communication link between the remote measurement-control units and the centralized master system. Many a times, sending personnel in remote locations for troubleshooting and service could be inconvenient, risky and expensive as the case may be either in industrial production sites or in electrical grid networks. In such situations, communication systems analogous to instrumentation telemetry links could become crucial and preferable. Depending upon data rates, messaging frequency, and security-latency requirements such systems could be designed and implemented to suit the customized needs.

If the SG communication system could be modeled and designed analogous to instrumentation telemetry system, the under mentioned benefits of instrumentation telemetry could be leveraged for the SGs:

(i) Reduction in operational costs.
(ii) Reduction in repair costs.
(iii) Reduction in labor costs.
(iv) Increase in system knowledge and situational awareness.
(v) Increase in equipment life.
(vi) Increase in regulatory compliance.

This paper is an outcome of our effort to model the SG communication system as an instrumentation telemetry system

and to survey and present the summary of recent works related to critical applications and parameters affecting the final technological design and performance of SG. Generally, the design of instrumentation telemetry starts with identification of 'critical applications' and 'critical parameters'. Critical applications of the SG are the major functional blocks of SG architecture that constitutes the basic structure of the SG and Critical parameters of the SG are the important parameters of SG that indicate the qualitative specifications of the design and performance of the SG. Post studies of literature, under-mentioned have been identified as critical applications and critical parameters for SG, listed in Table 1.3 given below.

1.3. Brief summary of remaining sections

The remaining paper is organized as follows. In Section 2, AMI, monitoring and automation of substations, power network monitoring, HAN, DR and Integration of solar PV have been presented as *critical applications* and along with basic details, review of recent research works on them have been summerized. Similarly, in Section 3, Reliability, Scalability, Interoperability, Congestion, Energy Efficiency, Latency and Security have been presented as *critical parameters* and along with basic details, review of recent research works on them have been summerized. The paper finally ends with useful conclusions and list of references utlized at the end.

2. Review on critical applications of smart grid [7–75]

2.1. Advanced Metering Infrastructure (AMI) [7–17]

AMI includes AMR and is one of the major and most critical applications of SG. It consists of smart meters that monitor power consumption, communicate with utility and control the appliances for optimized energy consumption and efficient data processing. AMI helps for financial benefits, improved services and opportunities for consideration of environmental concerns. Smart meters have bidirectional communication between consumer and utility for recording of energy consumption, communicating the data to the utility, service connect and disconnect switches with capability to measure power disturbances. Meters measure and record energy usage data at configurable sampling intervals (atleast once daily), and update it to both consumer and utility for billing and other purposes. Head-end systems (HES) are essential components of AMI communications networks. The function of HES is to manage data communications between smart meters and other information systems including Meter Data Management System (MDMS), customer information systems, outage management systems, and distribution management systems. The HES via backbone network and DCUs, transmits and receives data, sends operational commands to smart meters, and stores interval load data from the smart meters to support customer billing. There is no standard approach or configuration till now for design and development of communication networks to support AMI operations. Utilities use two-layer hybrid network systems to communicate between HES and smart meters. Typically, the first layer of the AMI network connects intermediate data acquisition points (e.g., smart meters,

Table 1.3
Smart grid critical applications and critical parameters.

Smart grid critical applications	Smart grid critical parameters
(i) Advanced metering infrastructure (AMI)	(i) Reliability
(ii) Condition monitoring and automation of substations	(ii) Scalability
(iii) Power network monitoring	(iii) Interoperability
(iv) Home automation network (HAN)	(iv) Congestion
(v) Demand response (DR)	(v) Energy efficiency
(vi) Integration of solar PV	(vi) Latency
	(vii) Security

Table 1.2
Smart grid applications and their major services [2].

Sr. No.	Smart grid critical applications	Services
1	Advanced metering infrastructure (AMI)	Interval measurement Load control Pre-payment Tarrif flexibility Communication and data security
2	Monitoring and automation of substations	Local/remote energy flow control Regional load management Automation of energy distribution Critical power parameters monitoring
3	Home automation network (HAN)	Local/remote control of devices Overall consumer load management Energy efficiency
4	Power network monitoring	Monitoring of power distribution Monitoring and control of losses Automation of Power flow routing
5	Demand response (DR)	Load adjustment Dynamic pricing
6	Integration of renewables	Integration of solar/wind/hydro Distributed generation Distributed demand response
7	Supervisory control and data acquisition (SCADA) system	Automated control of transmission and distribution Substation automation
8	Plug-in electric hybrid vehicle (PHEV)	Alternative energy source for vehicles Peak load levelling (Valley filling and peak shaving)

substations, etc.). The second layer of the AMI network consists of high-speed, fiber optic, Broadband Over Power Lines (BPL), microwave, and RF-cellular systems as backhaul networks to handle large volumes of data. The second layer of the network also utilize RF mesh and PLC communication networks to support SCADA operations. The selection of communications technologies depends on functional requirements, service territory topologies, and premise characteristics. Table 2.1 below lists the different types of communication technologies used to support AMI and meter data communications.

Architectural information: Diffrence in metering architectures between conventional and smart meter could be seen in Fig. 2.1, while Fig. 2.2 given below shows basic components of typical AMI system.

Network arhitecture of traditional AMR system has been shown in Fig. 2.3, while its modified version could be seen in Fig. 2.4 below in form of Wi-Fi based WSN network architecture.

Ref. [11] could be studied to have clear and detailed view of specific requirements and standardized approaches for smart meter, power consumption information collection device, construction scheme of network communication technology, business data management and application system. ZigBee and D-Bus based distributed power consumption measurement system in [12] claims to be better from the points of view of reliability and programming language support. Design of web-based multi-channel power quality monitoring system in [13], smart metering that provide the necessary voltage information quickly from all monitors to master head end to establish a near real-time control in [14] with OLTC voltage control strategy could also be referred. Typical application of cooperative transmission for the meter data collection in SG could be studied in Fig. 2.5, wherein the power consumption demand from the nodes has been measured by a smart meter and transmitted to MDMS through the DAU (also known as DCU) using wireless broadband access.

In [16], an approach of using unmanned vehicles for AMR applications in rural areas has been presented for wide area with small, but scattered customer density. The merits of the proposed system include non-requirement of regular network infrastructure and manpower, low operational cost, flexibility and online system management. For in-depth study of power system problems, implementations of FNET's applications in [17] could be reviewed that employs FDRs with GPS synchronized time-stamping and suitable communication networking. Compared to PMUs that utilize synchrophasor measurements for understanding, forecasting, or even controlling the status of power grid stability in real-time, the proposed scheme claims to be more efficient.

Table 2.1
AMI communication technologies [77].

Wired	Wireless
Fiber optic	Satellite
Broadband over power line (BPL)	Radio frequency (RF)—mesh networks
Telephone dial-up modem	RF—point to multipoint
Power line carrier (PLC)	RF—Microwave
Digital subscriber line (DSL)	RF—Cellular

2.2. Condition monitoring and automation of substations [18–30]

Condition monitoring (CM) is the major component of predictive maintenance and is process of monitoring important parameters of condition in machinery (vibration, temperature, etc.), in order to identify a significant change which is indicative of probable fault under development. CM helps in planning scheduled maintenance, or prior actions to prevent failure and avoid its probable consequences, so that conditions that reduce nominal lifespan of

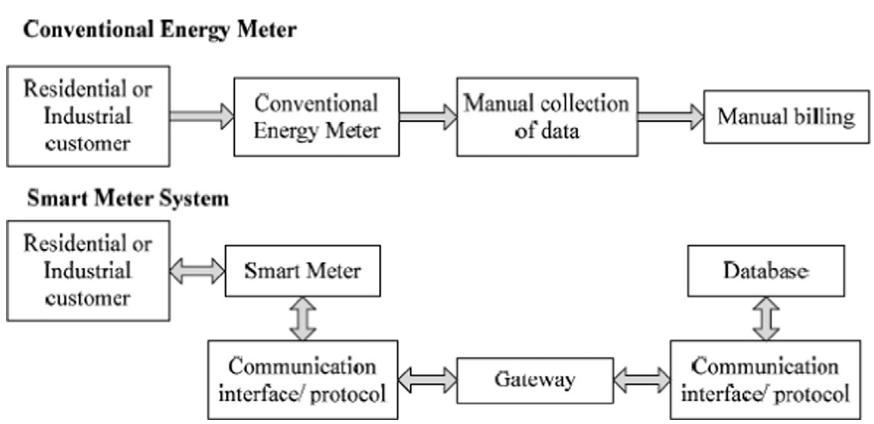

Fig. 2.1. Metering architectures of conventional meter and smart meter [7].

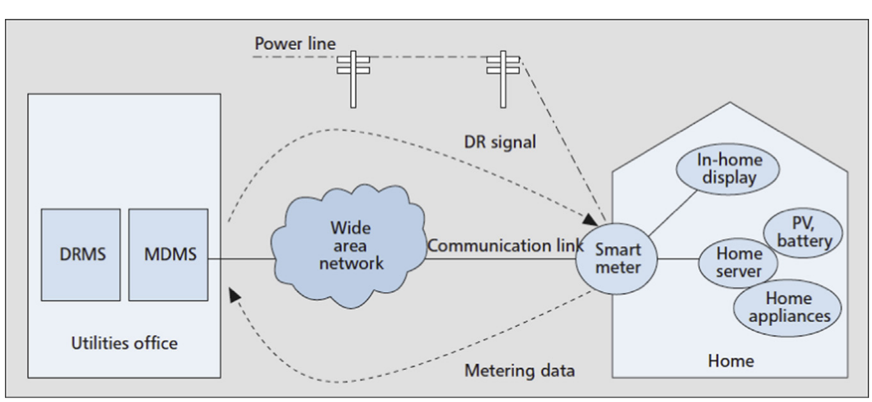

Fig. 2.2. Basic components of an AMI system [9].

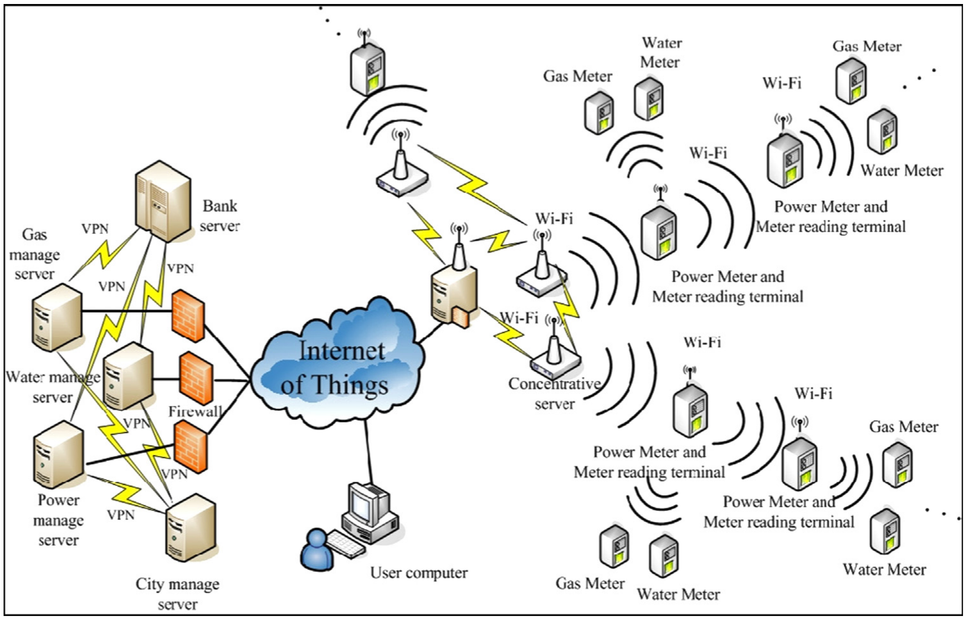

Fig. 2.3. Network architecture of traditional AMR system [10].

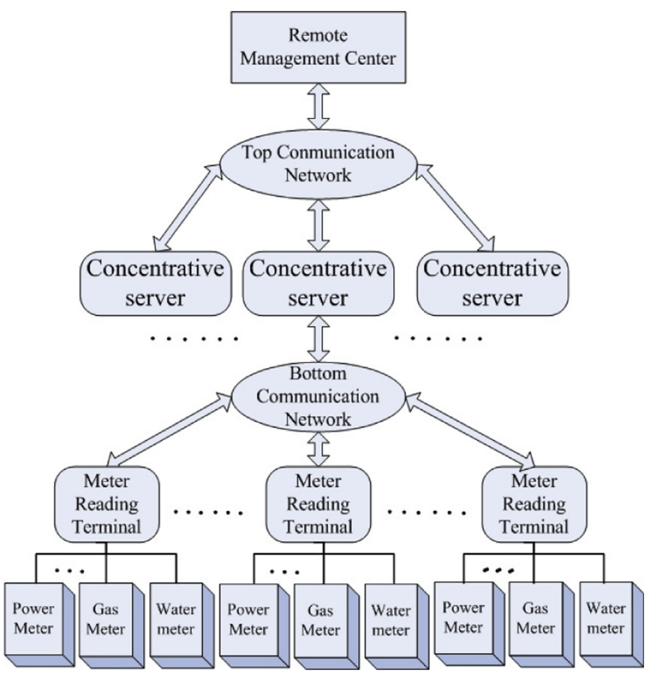

Fig. 2.4. Architecture of Wi-Fi WSN based AMR system [10].

costly and critical equipments, could be resolved before they result into large failures eventually.

2.2.1. *Condition monitoring of substations [18–27]*

Substations serve as 'last mile connectivity' in power distribution systems and their failure can cause complete blackouts in their regions of service. CM of substations include design and implementation of real-time condition monitoring system of substation assets, through combination of IEDs, smart sensors, secured communication / open protocols and 'intelligent' head end user-friendly software. The scope of this system include partial discharge in transformers; GIS; temperature monitoring of bushings, CTs and cables; monitoring of oil pressure-flow-level in transformers; moisture levels; dissolved gas analysis; cooling performance; load tap control; fault location and loadings on transformers; CM of circuit breakers, bushings, batteries, MV panels, capacitor bank, surge arrestor, reactor; and monitoring of SF6 gas density, cable temperatures, etc.

2.2.1.1. Condition monitoring of transformers. Transformers are the most critical assets of electrical transmission and distribution systems and their failures can occur due to various causes. In-service interruptions and failures of transformers usually result from dielectric breakdown, winding distortion caused by short-circuit withstand, winding and magnetic circuit hot spots, electrical disturbances, deterioration of insulation, lightning, inadequate maintenance, loose connections, overloading, failure of accessories such as OLTCs, bushings, etc. Transformer failures could cause power outages, personal and environmental hazards and expensive re-routing or purchase of power from other suppliers. CM of Transformers includes acquisition and processing of data related to important parameters of transformers by observing their deviations from their nominal values, to predict and prevent the transformer failures. Current approaches for condition monitoring of transformers have been summarized in Table 2.2.

2.2.1.2. Condition monitoring of relays and circuit breakers. Partial discharge, temperature, acoustic signals are utilized for monitoring condition of circuit breakers. Electrical field measurement based approaches have been utilized to detect variation of internal pressure of vacuum interrupters. Mechanical vibration signal has also been used to detect mechanical faults. Arcing time represents the state of dielectric component (internal pressure, impurity, etc.), while opening time stands for state of mechanical component.

Monitored data [9]

(a) Main data:
Data related to all the parameters to monitor consumption of electrical power distribution.
(b) Alternative data:
Relay data, alarm data, transformer load current, metering data, line current, line voltage, phase angle, harmonics, circuit breaker status, temperature data, pressure data, substation

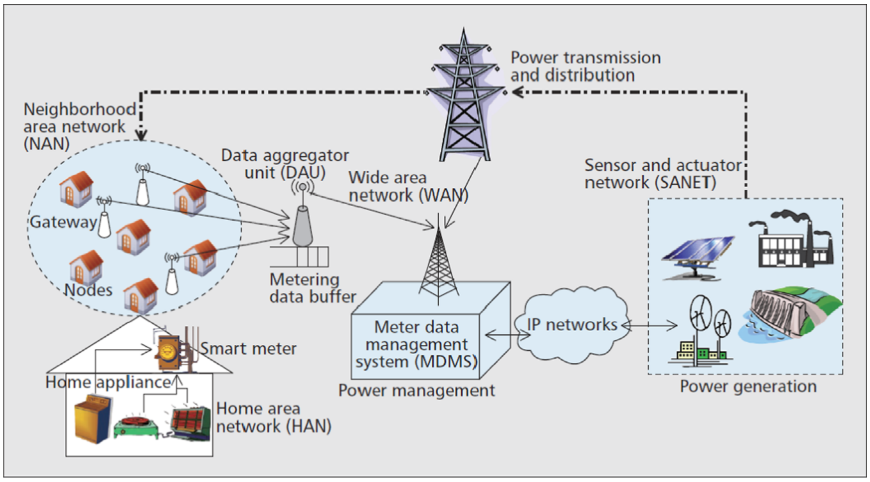

Fig. 2.5. Meter data collection in smart grid [15].

Table 2.2
Current approaches for condition monitoring of transformers [18–27].

Sr. no.	Approach	Methodology
1	Thermal modeling	Development of a mathematical model that predicts transformer temperature profile using the principle of thermal analysis Use of the thermal model to determine the top oil temperature and hot spot temperature
2	Dissolved gas analysis	Use of different gases as markers for different types of faults. Detection and classification of individual faults based on presence and concentration of gases
3	Frequency response analysis (FRA)	Non-intrusive very sensitive technique for detecting winding movement faults and deformation assessment caused by loss of clamping pressure or by short circuit forces Involves measurement of winding impedance of the transformer with a low voltage sine input varying in a wide frequency range
4	Partial discharge analysis (PDA)	PDs apparent as sharp current pulses at transformer terminals, whose nature depends on types of insulation, defects, measuring circuits and detectors used. PDs are initiated by the presence of manufacturing defects, or the choice of higher stress dictated by design considerations

security, demand (Watts, VARs, volts and amps), real-time data, KWWKQH, etc.

(c) Other data:
  (i) Oil Circuit breaker contact condition (contacts of current breaking and isolation).
  (ii) Cable oil leakage.
  (iii) Oil condition (tranformers and switches).
  (iv) Water in oil tanks.
  (v) Oil level in tanks.
  (vi) Battery condition.
  (vii) Transformer winding displacement.
  (viii) Temperature of components.
  (ix) Leakage of HV capacitor bushings.
  (x) Site security.

2.2.2. *Automation of substations [28–30]*

Fig. 2.6 below shows IEC 61850 based basic architecture of substation automation system utilizing different speed versions of wired ethernet at data acquisition and backbone levels.

Overall architecture of substation automation system shown in Fig. 2.7 below can be split into three major levels as summarized in Table 2.3 given below.

2.2.2.1. Communication subsystems for substation automation [29,30]. Overall communication for substation automation can be split into main and auxiliary communication as mentioned below:

(a) Main communication: includes data communication for—
  (i) SCADA.
  (ii) EMS.
  (iii) Control room automation system.

(b) Auxiliary communication: includes data communication for—
  (i) Distribution management system.
  (ii) Enterprise WAN.
  (iii) AM/FM/GIS systems.
  (iv) Revenue metering systems.
  (v) Feeder IEDs.
  (vi) Trouble call management.
  (vii) Regional management system.
  (viii) Demand response system.
  (ix) Customer information systems.
  (x) Protection systems.

2.2.2.2. Communication requirements for substation automation [29,30]

(i) High-speed IED to IED communication.
(ii) Networkable throughout the utility enterprise.
(iii) High-availability.
(iv) Guaranteed delivery times.
(v) Standards based.
(vi) Multi-vendor interoperability.
(vii) Support for voltage and current samples data.
(viii) Support for file transfer.
(ix) Auto-configurable/configuration support.
(x) Support for security.

Applications of WSNs have grown quite significantly in recent times in condition monitoring and automation of substations. Self-calibrating WSN of radiometers of [20] could be used as a lowcost approach to detect PD radiation for real-time condition monitoring,

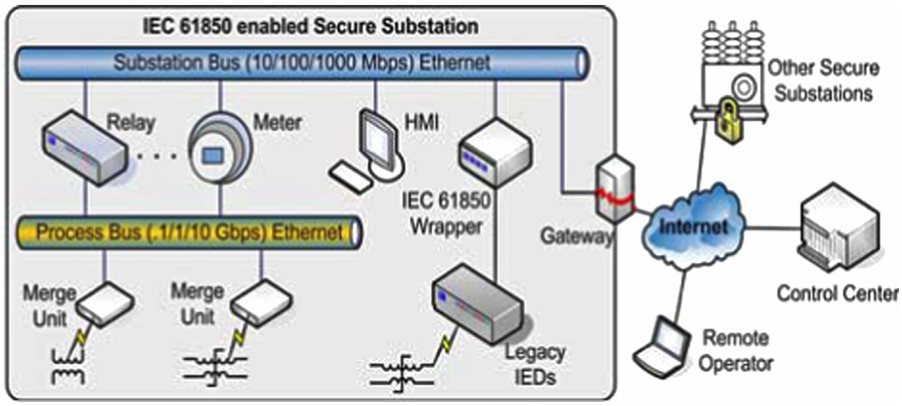

Fig. 2.6. Basic architecture of substation automation system [29].

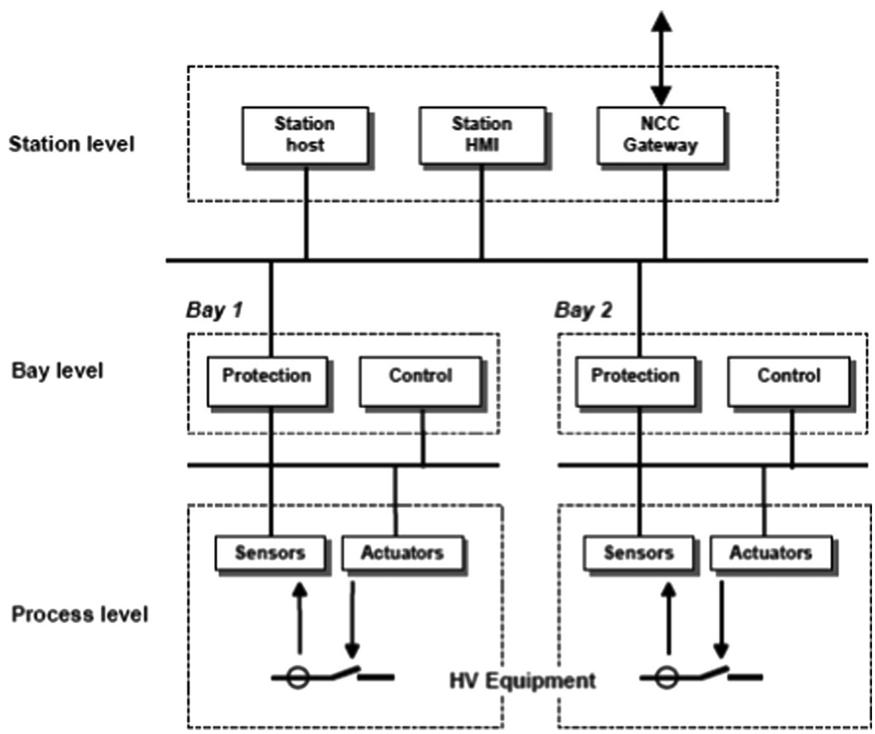

Fig. 2.7. Logical scheme of three levels of substation automation system [30].

Table 2.3
Major levels in substation automation architecture [28–30].

Sr. no.	Level	Hierarchy	Details
1	Process level	Lowest level	In this level, switchgear equipments are located with the necessary sensors and actuators to monitor and operate the switchgear. This level also contains devices like circuit breakers, current transformers, etc. At this level, IEDs, such as intelligent sensors and actuators could also be found, that are connected to LAN based process bus
2	Bay level	Middle level	In this level, protection distributed control equipments are located that are generally hardwired to bay level. Data basically consists of binary and analog I/O information such as voltage and current transformer outputs and trip controls from the protective relay
3	Station level	Highest level	In this level, centralized system computers, HMI and gateways for connections to NCC are located

asset management and operational optimization. Similarly, another WSN in [21], with its sink able to communicate with the utility's control system, could be deployed to aquire substation data to achieve intelligent management of data acquired and to allow, detection of faults as well as, to prolong the sensor nodes' lifetime using agent-based algorithm. Online monitoring and expert system of [22], for power transformer condition monitoring could be referred for complete data management, analysis algorithms and diagnosis functions. Role of IEC 61850 for interoperability between IEDs of different manufacturers has been well discussed in [23]. In [24], the integration of an agent-based WSN with an existing agent-based condition monitoring system has been proposed and demonstrated that MASs could be extended down to the sensor level, while considering the reduced energy availability of low-power embedded devices.

Requirement for a standard-compliant concept for a reconfigurable software architecture used in IEDs has been presented in [25] along with simulation and case study. DSP based design with GPRS for remote monitoring of prefabricated substation could be referred from [26] that collects and transmits the energy parameters and monitors-controls the substation. In [27], wireless sensor communication model for overhead transmission line monitoring has been proposed and its performance has been evaluated using testbed. The proposed model results into reconfigurable network based on the application requirements to deliver required information to substation. Overview of recent trends in the protective relaying area could be studied from [28] including the coverage on substation automation, testing practices and standardization. Fig. 2.8 below depicts timing requirements for various smart grid applications.

2.3. Power network monitoring [31–35]

Power quality has increasing role in deregulated electricity supply markets. For assessment of performance of utilities, a power quality database can act as a benchmark. This can be achieved via benchmarkmg of a utility's voltage dip performance level and comparison with national-international benchmarking studies. Thus, they can provide system improvement based on the indices. Also, power quality problem affects the power reliability of demand side especially for those bulk tariff consumers or large property management companies since they manage many different properties. Therefore, measurement and collection of power quality data for both supply and demand side are extremely important. Monitoring of events in the power system provides a great deal of insight into the behavior of the system. Events with impact on the entire power system typically occur in or near the transmission network and are therefore best monitored at power networks. For this, sensors are deployed on the location close to the poles/towers supporting a long overhead transmission lines on each span. Recently, 'Optimal sensor deployment to ensure robust and unique localization of line faults' has emerged as one of the popular research areas in SG.

Refs. [31,32] could be referred to get an overview of design of web-based multi-channel power quality monitoring system for a large network and an innovative framework of Pervasive Service-Oriented Networks (PERSON). The later has been proposed to address the challenges of conventional EMS. A three-step control methodology proposed in [33], to manage the cooperation between the novel and emerging technologies for distributed generation, distributed storage and demand-side load management, has been focused on domestic energy streams. In this approach, (global) objectives like peak shaving or forming a virtual power plant could be achieved without harming the comfort of residents. Close agreement between voltage and frequency at low and high voltage levels during a remote and a nearby fault in the transmission network has been documented in [34]. It also opines by support of high quality experimental data that valuable information about the transmission system could be obtained at lower voltages. An application of WSNs in distributed generation in [35] proposes a Find Reliable Link (FRL) scheme to have a reliable communication with minimal end-to-end delay during the event of next hop node failure. It aims to enable the system to make a quick recovery from sensor node failures or link failure due to obstacles thereby reducing the end-to-end delay.

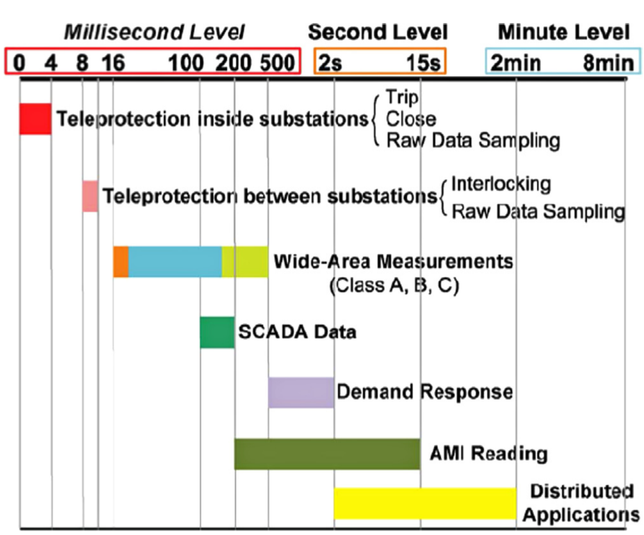

Fig. 2.8. Timing requirements for various smart grid applications [75].

2.4. Home automation network (HAN) [36–48]

SG initiated dynamic changes and new business contexts in the utility infrastructure, especially in demand side, the conventional energy customers have now been scaling up their role as the energy prosumer who can contribute by generating distributed power with renewable energy resources and create income by trading the power back to either utility or to power exchange market. Recent energy shortages have reinforced the requirements for highly optimized energy management, wherein consumers try to use lesser power and save money, especially during peak demand rate periods. HAN is an intelligent instrumentation based automation network within the premises of a house or building enabling devices wherein various electrical loads communicate with each other directly or via central system and dynamically respond to externally sent signals (i.e. price variations during peak periods). This type of network, is generally characterized by a low data rate requirement and provides communication infrastructure under the purview of each smart meter setup by utility. Energy savings and user satisfaction are two major design considerations for modern HAN systems. The purpose of HAN is to create and maintain comfortable, safe, energy efficient, economical and environment-friendly living environment by connecting home elements like sensors, appliances and thermostat, etc. For HAN, both wired as well as wireless communication technologies are in practice today. By using wired PLC technology, electric home appliances could be monitored and controlled through alredy existing domestic power lines, while in wireless options, WSN are gaining popularity due to their obvious merits.

For learning regarding MAC protocol development for HAN using ZigBee and Wi-Fi MACs with CSMA/CA mechanism, [36] could be referred wherein along with discussing latency and energy efficiency problems, design of a tree-based TDMA MAC protocol has also been discussed. Similarly, in [37], advantages of the digitalSTROM® topology have been presented for optimization of modulation schemes for miniaturized implementation and quantified the level of interference caused by typical home appliances. An embedded Remote Monitoring and Controlling Power Socket (RMCPS) has been developed in [38] with high suitability for automatic power management of home electric appliances. The design has been presented as replacement of the classical design of PC with a Web server construction with remote user connectivity and it claims merits like low cost, low electricity consumption, small volume and convenient installation. For existing buildings, in order to save upon the cost of expensive cables, existing powelines could be utilized to carry HAN data using wired PLC technology that also maintains aesthetics. For further details for the same, [39] could be studied that describes PLC and smart metering based Home Energy Management System (HEMS) to provide detailed information of energy consumption patterns and intelligent home appliance control with easy-to-access information on home energy consumption in real time, intelligent planning for controlling appliances, and optimization of power

consumption at home. Similar to [38] in [40], a transmission protocol with two-way recognition and control service for a home grid could be studied, wherein a household appliance could be plugged into a wall socket and smart meter could start reading the real-time electronic energy information and control signals. Based on Multi-objective optimization in [41], for saving money and comfortable living, an optimal dispatching model has been developed as Smart Home Energy Management System (SHEMS) with Distributed Energy Resources (DERs) and intelligent domestic appliances. A methodology for evaluation to investigate the performance of wireless technologies for device interconnections under HAN in wireless smart homes and indoor scenarios has been presented in [42]. A similar approach using an embedded system using PLC technology, to monitor and control home appliances and PPCOM (PLC Power-Controlled Outlet Module) has been described in [43] to integrate the multiple AC power sockets. Web based user interface enables the user to monitor-control the home appliances using embedded home server and internet. Building Energy Management Systems (BEMS) presented in [44] to support Demand Side Management is based on real-time platform, duly validated using A Power-Hardware-In the-Loop (PHIL) testbench. Ref. [45] could be studied for design of smart home device descriptions and standard practices for demand response. Load management "Smart Energy" applications have also been presented along with ZigBee based HAN system design that provides intelligent services for users, duly validated using a real testbed. A smart home computing platform architecture has been presented in [46] to extend smart home network be SG compatible. The proposed architecture supports bidirectional communication with home appliances via a public mobile network, locally via a control panel and remotely via the home owners' mobile phones. Ref. [47] assesses the feasibility of using the TV White Space (TVWS) spectrum for home networking services and compares the performance with other license-exempt spectral bands, e.g. 2.4 GHz and 5 GHz band. Limitations of TVWS in presence of interference have also been studied. Overview of applicability of WSNs for electric power systems, their opportunities and challenges have been included in [48]. Performances of an in-Home Energy Management (iHEM) and Optimization-based Residential Energy Management (OREM) have been compared to minimize the energy expenses of the consumers.

2.5. Demand Response (DR) [49–64]

DR, DG and DES are the core subsystems of the emerging SG paradigm. Demand response is the management of electricity consumption of customer in response to vibrantly changing supply conditions of SGs. In Demand response mechanisms, the shut off request is explicitly made, whereas the demand devices passively shut off when the grid observes the stress. Demand response curtails the power used and it can also start on-site power generation which may or may not be connected in parallel to SG. The full potential of demand response could be significant, but its exploration has still remained a challenge mainly due to the non-homogeneity and the distributed nature of energy resources.

A pricing policy mechanism in [49], based on the provider's prices announcement, controls the appliances remotely during peak hours of the day, on the other hand, a synergistic DR approach in [50], includes asset management and service reliability using smart metering, AMI and MDMSs. Existing and evolving DR programs at different ISOs/RTOs and the product markets have been summarized in [51] with challenges and solutions. Three step control strategy of [52] has been designed to optimize the overall energy efficiency and to increase the amount of generation based on renewable resources with the ultimate goal to reduce the CO_2 emission resulting from generation electricity. Ref. [53] could be studied for design of methodology for demand-responsive energy management system to control domestic energy resources in SG based on dynamic tariffs and quality of service constraints. A system developed under the BEE Project for predicting the usage of household appliances has been presented in [54] based on wireless power meter sensor network. A NAN-level DR program (also referred as Coordinated Home Energy Management (CoHEM)) presented in [55] for coordinating HEMS of residential customers to opportunistically consume spikes of locally generated renewable energy. MPC is used to modulate the aggregate load to follow a dynamically forecasted generation supply. Both centralized and decentralized deployments of CoHEM have been compared and merits of CoHEM model could be observed in absorbing the fluctuations in the generation output of distributed renewables. Instead of complex systems based approach for large installations, in [56], the smart controller has been used to reduce energy consumption, which could be installed on the electric plug of the electric appliance to grasp the energy amount used in the electric appliance and to deliver the same data to AMI/EMS. Additionally, developed experimental system for light control controls illumination according to the load change and saved energy effectively. The impact of a DSM scheme has been evaluated in [57] that shift residential high-power appliances (loads) to reduce the overall peak of households connected to the same LV feeder. For real-time tracking of operating states of the distribution system connected with DGs, in [58], a new network-enabled, real-time monitoring strategy has been presented that claims to be fault-tolerant and possesses features such as classical cascading, star and ring architectures with real-time data acquisition. In [59], demand response is optimally scheduled jointly with other resources such as distributed generation units and the energy provided by the electricity market, minimizing the operation costs from the point of view of a virtual power player, that manages these resources and supplies the aggregated consumers. Various DSEM scenarios have been analyzed in [60] that become available with sensor network web services based on a smart home with WSN and live database. Sepia, a self-organizing real-time electricity-pricing scheme has been proposed in [61] that compute the price of a kilowatt-hour of electricity as a function of consumption history, grid load and the type (hospital/commercial/industrial etc.) of the customer. The details of pricing scheme and how this scheme could potentially alter the consumption patterns—have been demonstrated using simulation. TOU-aware energy management in a smart home with WSHAN in [62] could be referred for analysis of its impact over peak load. It claims reduction in the use of the appliances in peak hours and savings in the energy bills for consumers. The Appliance COoRDination (ACORD) scheme has been presented in [63] that uses the in-home WSN and reduces the cost of energy consumption. The proposed ACORD scheme has been aiming to reduce cost of energy by shifting consumer demands to off-peak hours. Appliances have been using the readily available in-home WSN to deliver consumer requests to the EMU that schedules consumer requests with the goal of reducing the energy bill. Novel control scheme for automated demand response mechanisms in [64] has been based on the application of predictive control techniques to support large-scale implementation of DR programs, and capturing the planning phase, the real-time operations, the verification of the energy and service provision, and the financial settlement.

2.6. Integration of solar PV [65–77]

Transformation to SG allows the electric grid to be more adaptive to dynamic behavior of renewable energy and distributed

generation, helping both consumers and utilities to access these resources and harvest their benefits. Communication systems are crucial technologies, which enable the accommodation of distributed renewable energy generation and play extremely important role in monitoring, operating, and protecting both renewable energy generators and utility power generation systems. We have considered Solar PV among different renewables to study this SG application. The major part in a solar PV system is the conversion stage and its characteristics dominate the behavior of the solar PV system. Intelligent interfaces to a PV system that allow the grid to handle two-way flows of power and information are required and would provide seamless integration. Rooftop photovoltaic power generation is one of the important application forms of solar photovoltaic power generation technologies. With the constant enlargement scale of the rooftop photovoltaic power generations, the measurement and control system, and hence, real-time remote monitoring became specifically quite important.

An experimental ad-hoc WSN in [65] designed as an anti-theft alarm system based on accelerometers, WSN, serial communication and PC with an open source operating system and software. The system has provisions to generate SMS, e-mail and audio-visual alarm annunciation. Ref. [66] could be referred for a novel rooftop photovoltaic power generation measurement and control system based on Internet of Things (IoT) to provide good control platform for theoretical values and actual engineering significance. In [67], some communication technologies have been reviewed for grid integration of renewable energy resources. Analysis of impacts of rooftop PVs at different penetration levels on the performance of distribution transformers and residential networks could be studied in [68] that might lead to an overall reduction in the reliability and economy. Management of intelligent distribution system with the renewables, using remote wireless monitoring and control could be studied in [69] for monitoring and control of 50 kW PV system installed remotely (about 1 km) in campus of the Korea University of Technology and Education. Similar wireless remote monitoring and control system has been described in [70] for a solar PV-DG to support microgrids applications. Similarly, design of an autonomous wireless sensor node with a photovoltaic energy source has been presented in [71] in form of a proof of concept prototype for monitoring for a small solar panel. In [72], the SG features have been reviewed with a focus on renewable energy integration. Real-time diagnostic monitoring system of PV power plant described in [73], aims to create a stand-alone photovoltaic generator that could be easily relocated in remote areas to evaluate the feasibility of photovoltaic energy applications. Hardware, firmware and application interface design for a wireless node and base station for environmental application have been discussed in [74], to characterize photovoltaic panels in harsh environmental conditions.

Table 2.4 below presents voltage fluctuation parameters and their recommended monitoring frequency. This table could be used to study and fix up the sampling rates. Tables 2.5 presents network requirements and Fig. 2.8 depicts timing requirements for various smart grid applications, which could be mainly useful in network design.

Table 2.4
Voltage fluctuation parameters and their monitoring frequency [14].

Voltage fluctuation parameter	Monitoring frequency
Power frequency	Weekly
Supply magnitude	Weekly
Flicker	Weekly
Supply voltage dips	Yearly
Short/long interruptions	Yearly
Temporary overvoltages	Yearly
Voltage unbalance	Weekly
Voltage harmonics	Weekly

3. Review on critical parameters of smart grid [76–192]

3.1. *Reliability* [76–107]

Reliability of any electrical grid depends upon service intterruptions or outages, power quality disturbances; and frequency, duration and influence range of aforementioned problems. Prime factors affecting SG Reliability include coordination of network monitoring and control, resource type balancing, congestion and throughput of communication infrastructure, renewable energy resources and their integration, load management or demand response, storage devices, electric transportation, electric service interruptions, voltage reductions, acts of sabotage, unusual occurrences that can affect the reliability of bulk power delivery systems, and fuel problems. Radial operating status, aging infrastructures, poor design and operation practices and high exposure to environmental conditions are the most frequently encountered issues by the electric power distribution systems and are the major contributors to the consumer reliability problems. Generally, about 80 to 90% of the customer reliability problems are originated from the electric power distribution systems. Such statistics always reinforce the electric utilities to look after solutions that can be used for reliability enhancement of the electric power distribution systems. There are a large numbers of solutions available to electric utilities for distribution system reliability improvements. Electric utilities have traditionally improved the distribution system reliability through simple measures such as tree trimming on a regular basis, construction design modification, installation of lightning arresters, use of animal guards, replacing overhead bare conductors by covered conductors or underground cables, protection scheme modification, and so on. In addition to these conventional solutions, there are some other advanced reliability improvement measures that nowadays are categorized as SG technologies. Major SG technologies applicable for distribution system reliability improvements are fault passage indicators, fault locator schemes, substation automation, feeder automation,

Table 2.5
Network requirements for various smart grid applications [19].

Application	Network Requirements				
	Bandwidth	Latency	Reliability	Security	Backup Power
AMI	10–100 kbps/node, 500 kbps for backhaul	2–15 s	99–99.99%	High	Not necessary
Demand response	14–100 kbps per node/device	500 ms—several minutes	99–99.99%	High	Not necessary
Wide area situational awareness	600–1500 kbps	20 –200 ms	99.999–99.9999%	High	24 h supply
Distribution energy resources and storage	9.6–56 kbps	20–15 ms	99–99.99%	High	1 h
Electric transportation	9.6–56 kbps, 100 kbps is a good target	2 s–5 min	99–99.99%	Relatively high	Not necessary
Distribution grid management	9.6–100 kbps	100 ms–2 s	99–99.999%	High	24–72 h

distribution automation, fault current limiters and dynamic voltage restorers.

Availability of the various reliability enhancement solutions is both an opportunity and a challenge for electric utilities. They have an opportunity to find the right solutions for their own reliability problems. But, each electric utility is different from another one and has its own set of failure causes for distribution system problems. In addition, the design history and the network configuration have large impacts on the specific solutions to be selected. Therefore, the challenge for electric utilities, especially in the competitive electricity market, is to identify and evaluate potential reliability reinforcement schemes and then determine and prioritize those appropriate for implementation. Reliability assessment of the electric power distribution systems has received a great attention over the past decades. Nowadays, several commercial software that are available to electric utilities that can be used for reliability assessment of the electric power distribution systems. Such software usually work based on one or a combination of well-developed reliability assessment techniques such as the analytical simulation approach and the Monte-Carlo simulation approach. It is, therefore quite necessary to develop a reliability evaluation approach for predicting the reliability performance of the electric power distribution systems, when employing such sophisticated solutions. The reliability of modern power distribution systems is dependent on many variables such as load capacity, renewable distributed generation, customer base, maintenance, age, and type of equipment. QoS being one of such requirement, different smart grid applications and their QoS specifications have been summarized below in Table 3.1.

A method for quantitative assessment of SG reliability in [77] evaluates the combined behavior of distribution grid, communication infrastructure and control functions. The method could be used in SG design and planning for comparing expected reliability of design alternatives and for identifying risk areas, weaknesses and their impacts on overall reliability. Similarly, another reliability method and key technology of the SG have been introduced in [78] based on conversion of quantitative and qualitative methods by cloud theory. Theoretical aspects of statistical forecasting presented in [79] based on time series analysis using historical consumer load data combined with local weather forecasts to predict an increase in consumer demand to enable utility companies to make informed decisions in purchasing additional capacity and/or sending out selective consumer alerts. Reliability maintaining be challenging while achieving flatter net demand by getting ideal mix of major energy resources, hence in [80], grid wide IT architectural framework has been presented to meet those challenges while facilitating modern cyber security measures and supports a multitude of geographically and temporally coordinated hierarchical monitoring and control actions. SAX (Symbolic Aggregate approXimation), an advanced intelligent computational tool in [81], to characterize and analyze the large amount of data associated with wide variations in network behavior along with pattern recognition for dealing with network asymmetry, load unbalance, single-phase solar PV integration and their impacts on upstream networks and assist in making right and timely decision to mitigate adverse impacts of solar PV. Ref. [82] aims to develop a new, Practical Power Reliability Index (PRI) for enterprise-level power grids, that is data-driven different from traditional evaluation methods and takes advantage of smart meters that are capable of recording various power quality indicators at selected monitoring points, estimates instantaneous network reliability, using measurements fro smart meters and customized algorithms based on Expectation Maximization (EM) and Monte Carlo Expectation Maximization (MCEM). Systematical reliability and security assessment process in [83] follows a three-level assessment hierarchical architecture for the electric power develops an application to assess the reliability and security. Ref. [84] addresses the impact of situational awareness and controllability on power system reliability assessment. A methodology has been proposed to simulate a situation in which a limitation of either or both monitoring and control functions could spread the consequence of power system events throughout the grid and based on a Wide Area Measurement System (WAMS) and analyzed on 9-bus and the IEEE 57-bus systems. A routing protocol (named Hybrid Wireless Mesh Protocol; HWMP) has been proposed in [85] from the perspective of transfer reliability, along with a new routing method for reliability enhancement to improve the routing reliability of 802.11 s-based SG mesh networking. In [86], models and methods for reliability analysis currently used have been discussed along with complications due to cyber layer and research directions. A complete suite of integrated risk and performance assessment tools in [87] for substation equipment has been developed and successfully demonstrated with the application of algorithms to power transformers and high-voltage circuit breakers. A cooperative communications approach to improve reliability of mesh networks in form of Opportunistic Forwarding Protocol (ORPL) has been realized in [88], as an enhancement on top of the Routing Protocol for Low Power and Lossy Networks (RPL), a connectivity enabling mechanism in AMI mesh networks. In ORPL, smart meter nodes select multiple candidate relays to facilitate reliable transport of smart metering data to the concentrator node. Moreover, it is designed to work in a distributed manner thereby ensuring scalability. Ref. [89] presents a concept, method, and implementation of utilizing PMU information to monitor the wide-area security of a power system and evaluates grid reliability and security on a system-wide basis. In [90], a reliability analysis of the wireless communications system in the SG to support DSM has been presented. Based on random failure of the system devices, availability performance is obtained and the cost of power-demand estimation error and damage of power distribution equipment have been estimated. Finally, redundancy design approaches have been presented for minimization of cost of failure as well as cost of deployment of the wireless communications system in the SG. Unit Commitment (UC) techniques have been applied in [91] for such a situation. Each of these units has associated variables like continuous ratings, start-up and shut-down characteristics, failure and repair rates, reliability indices etc. Ref. [92] presents a quantified reliability evaluation method for the backbone communication network in WAMS that is modeled using hierarchical structure based on evaluation using Markov modeling and state enumeration. The quantitative reliability assessment presented in [93] supports the decision makers when it comes to different alternative technologies using example of Ground Fault Neutralizer (GFN). The impact of the GFN protection scheme on the distribution network from a reliability point of view has

Table 3.1
Smart grid applications and their QoS specifications [76]. *Notations*: β=data rate, τ=time delay, and α=reliability.

Application	β (kbps)	τ (s)	α (%)
Smart metering (AMI)	14–100	2	99–100
Price signaling	9.6–56	2	99
Automated feeder switching	9.6–56	1–2	99
Demand response	56	2	99–100
Emergency response	40–250	0.5	99–100
Residential energy management	9.6–56	1	90
Building automation	16–32	1–2	90
SCADA	56–100	2–5	99
Distributed generation	9.6–56	2	99
Distributed management & control	56	2	99
Overhead transmission line monitoring	9.6–64	1	90
Outage management	56	2	99

been studied and popular reliability indices including SAIFI, and SAIDI have been used to measure the reliability using IEEE-RBTS as reference system. Ref. [94] quantitatively evaluates the reliability of modern power systems, which incorporates the impact of cyber network failures on the reliability of the power network. Two optimization models are introduced to maximize the data connection in the cyber network and minimize the load shedding in the power network to evaluate the impact of direct cyber-power interdependencies on the reliability indices based on microgrid application. Ref. [95] presents the view that the success of integrating SG concepts and technology will rely heavily on reliability of the existing bulk power system during its evolution. All-digital Special Protection System (SPS) architecture in [96] for the future SG is based on calculation of important reliability indices by the network reduction method and the Markov modeling method. Application of certain SG technologies to a distribution system and the impact on reliability has been focused in [97] and modeling some techniques using Monte Carlo simulation in MATLAB. Possible impact of DSM functionalities on the reliability improvement and formulation of novel reliability assessment procedures have been discussed in [98] along with comparing its results with traditional ones without DSMs and reliability matrices. Another methodology for assessing reliability performance of power systems with fully employed DSM and DG&S functionalities discussed in [99], allowing quantification in the most realistic manner standard set of indices reported annually to the regulators. The methodology extends conventional reliability assessment procedures to include equivalent network models, actual load profiles and empirical fault probability distributions in the analysis, allowing making a clear distinction between the short and long supply interruptions. Ref. [100] puts forward an architectural composition of SGs from a reliability perspective and initiates a discussion to identify the foreseeable challenges in quantitative reliability estimation. The paper also expresses an imminent need to evolve an integrated framework that can accommodate realistic reliability appraisals useful in decision making processes. As a precondition of self-healing control of SG, real-time operation reliability assessment and its analysis has been presented in [101]. Influential factors of operational reliability of the urban power grid, definition of assessment index and its calculation using Multi-Model technology has also been discussed. Results of simulation for an urban power grid support the capability of the assessment method. In [102], comprehensive node traversing algorithm and the formation of orthogonal method of path tracking algorithm have been discussed. Based on the path tracking algorithm method, Reliability Block Diagram (RBD) model has also been presented. The paper puts forward the reliability of the Guangdong electric power communication network. Ref. [103] investigates the risk assessment of the uncertainties associated with system generation in the operation planning horizon using probability models, projected load demand and MCS based Loss of Load probability (LOLP) calculation. Electric Power Data Network for the SG proposed in [104] along with comparative analysis on the information congestion degree based on artificial spider web and star topologies. Ref. [105] could be studied for probabilistic analysis and reliability assessment be combined to investigate the ability of a power system withstanding serious contingencies using state enumeration method, risk indices and power system security. Ref. [106] describes strategies explored to improve supply reliability in China by introducing On-line Distribution System Risk Assessment System (ODSRAS), designed to forecast the annual AIHC-1 in Xiamen with suggested framework and the HMI of ODSRAS with ability to improve reliability by risk theory. Impact of terrestrial radiation effects on the reliability of a SG analyzed in [107] also introduces the mechanisms of radiation effects on semiconductor devices and mitigation techniques.

3.2. *Scalability [108–115]*

In terminology of electronics (including hardware, communication and software), scalability is the ability of a system, network, or process to handle a growing amount of work in a capable manner or its ability to be enlarged to accommodate that growth. For example, it can refer to the capability of a system to increase total throughput under an increased load when resources (typically hardware) are added. A system whose performance improves after adding hardware, proportionally to the capacity added, is said to be a scalable system.

Technology based on Public Key Infrastructure (PKI) to the envisioned SG could be studied in [108] that provides permission and authentication to massive numbers of computational devices for providing scalability. Ref. [109] evaluates a local neighborhood market and investigates its scalability under different numbers of participants and different penetrations PV generation by simulating market operations under realistic production and consumption conditions. Scalability of three communication architectures for AMI in SG investigated in [110] by a new performance metric, Accumulated Bandwidth Distance Product (ABDP), representing the total communication resource usages by formulating an optimization problem for architecture, and then solving it by minimizing the total cost of the system considering both ABDP and the deployment cost of the MDMS, further validating the same by supporting results of simulation. Scalability of SG and principles for an efficient management of a massively distributed energy system based on small and variable energy resources could be studied in [111] along with simulation based evaluation and study of aspects of ICT management frameworks. To address the scalability challenges, a SEcure Data-centric Application eXtensible (SEDAX) platform presented in [112] for SG applications for scalable, resilient and secure data delivery and data sharing in WAN to scalably handle high volumes of data generated by both applications and sensors using the *Delaunay Triangulation* (DT) network, to yield cost effective communication in terms of overhead and memory. The authors of [113] have surveyed and concluded that there has been no well-known transport protocol that can support the characteristics required in a scalable and light-weight manner. A Scalable and Secure Transport Protocol (SSTP) has been proposed and presented in [114] to exploit the notion of a “State-token” which is issued with each server message and which is subsequently attached to corresponding client message delivered to the server. Compared with existing well-known transport and security schemes, SSTP enables scalable server deployments and computation/memory overheads significantly reduced.

3.3. *Interoperability [115–129]*

Interoperability is about the characteristics of instruments, equipments and systems to connect and work with competibility without loss of necessary and sufficient functionality. Higher level interoperability simplifies configuration and less frequent maintenance leading to rapid integration, reduced efforts and hardware expenses, visibility, performance and novel methods for upgradation. Sharing and standardization of specifications raises vendor competition and creativity of solutions to newer levels and thereby add new value benifitting everyone. SG interoperability increases healthy competition among vendors, creativity, more options, lesser expenses and reduced financial risk due to technology or vendor obsolescence, and enhances the overall intrinsic value of automation with significant improvement in reliability. Unfortunately, interoperability in practice, cannot be achieved by a single organization, but it necessitates collaborative efforts from

various organizations including utilities, regulator, standardization authorities, manufacturers, etc.

Recent SG designs have been observed following top-down architecture, specifically about management of consumer power consumption, that could be excessively expensive and necessitates substantial confidentiality compromises. Such designs could restrict customer choice and deaccelerate the innovation. An alternative approach of SG design presented in [115] using internet based model follows a decentralized, bottom-up design that enables consumer choice and supports social objectives with minimal centralized management. Interoperability testing described in [116] at national grid to prepare SG pilot demonstration, system level testing and technical evaluation of distribution protection and control equipment with automated fault isolation and system restoration capabilities. Levels of Conceptual Interoperability Model (LCIM) in [117] presents the context of supporting composability, interoperability, and integratability of systems and identifies the architecture constraints for enterprise and systems architectures. Here, enterprise architectures set the conceptual context for the systems, the system architecture defines the implementation details with importance, identification and storage of metadata. Overall SG model from both architectural as well as functional prospects presented in [118] and interoperability (modeled as a cooperating multi-agent system) has been discussed. Essential need for business alignment with standardised information models such as the IEC Common Information Model (CIM) has been focused in [119], to leverage data value and control system interoperability. An interoperability maturity model has been drafted in [120], and experience is being gained through trials on various types of projects and community efforts, describing the value, objectives and nature of interoperable maturity models with comparative analysis and lessons learnt. An Interoperability Test Platform (ITP) in [121] for interoperability, functional and penetration tests in equipment also implements ABNT NBR 14522 protocol to demonstrate the protocol simulation and monitoring resources of ITP with capability to test ZigBee and DNP3 protocols. In [122], to highlight the issue of device level integration and encourage communication and the development of a SG interoperability community, created Conceptual model of an Interoperability Context-Setting Framework, reported by the GridWise® Architecture Council (GWAC) in [122], which is helpful to explain the importance of organizational alignment in addition to technical and informational interface specifications for smart grid devices and systems, is a step toward building an SG Interoperability Maturity Model (SGIMM). The objective is to create a tool or set of tools that encourages a culture of interoperability in this emerging community. Software models for SG presented in [123] are necessary to quantifiably evaluate, monitor the progress and plan for the realization of SG and SGIMM, Investment model, Maturity model and Conceptual model are discussed. Approach presented in [124] defines a semantic framework which includes (1) a semantic model defined in a powerful ontology language and (2) the proper processing components as the means for interpreting data and for inferencing implicit knowledge. Additionally, both these parts need to be integrated into the grid node design for supporting the systems interoperability in all localization and decision levels of the SG. Hierarchy to reach the interoperability of future smart grid is presented in [125] by introducing compliant levels in a pyramidal model, modeling interoperability layers using a button-top approach, ZigBee or 6loWPAN, autonomous smart sensors based on IEEE 1451: NCAP, WTIM for small energy harvesting devices deployed in smart homes and energy utilities, to improve the efficiency, reliability and customer cost savings. The main aim of [126] is to discuss the usage of IEC 61850 together with the IEC 61499 reference model for distributed automation and the development of a related IEC 61499 Compliance Profile

for SGs. To prove the feasibility of using decentralized multi-agent control logic in the automation of power distribution networks, in [127], the utility network is modelled as communicating logical nodes following IEC 61850 standard's architecture and implemented by means of IEC 61499 distributed automation architecture. The system is simulated in an IEC 61499 execution environment combined with Matlab and proven to achieve simple fault location and power restoration goals through collaborative behavior and interoperable devices. Status of IEEE P2030 series of standards development, the IEEE 1547 series of standards publications and drafts, and insight on systems integration and grid infrastructure could be referred from [128].

3.4. Congestion [129–138]

Popular meanings of the term congestion are overcrowding or overaccumulation or clogging. Efficient congestion management is a key priority for any SG in line with its legal responsibility for reliable grid operation. There are two major types of congesions with reference to the SG—Congestion in Power Transmission and Congestion in Data Communication.

3.4.1. Congestion in power transmission

Electricity traders and producers export excess power produced to other regions or procure shortfall in the power from other regions outside their territory of work. They use grid network to transport it among regions. Due to limitations of transmission capacity of the grid network, congestion occurs in the grid. Congestion management aims primarily to prevent this congestion from happening, by active management of transmission capacity, thereby keeping the grid stable and prevents outages. Auctions are the key tools of congestion management, they keep transmission capacities in cross-border traffic auctioned off, and thereby guarantee transparent allocation to keep the grid stable and provide secured and reliable electrical supply.

3.4.2. Congestion in data communication

Congestion, in the context of data networks refers to a state of network, where a node or link carries excessive data that deteriorates service quality of overall data network, resulting in queuing delay, frame or data packet loss and preventing new connections. Due to congestion in data communication, response time rises sharply, network throughput reduces, bandwidth looks insufficient and communication channels get overcrowded. Congestion generally results from limited network resources, especially router processing time and link throughput. Network congestion often leads to congestion collapse. To solve congestion problems, many a times, latency-bandwidth tradeoffs are required. There are four major techniques for congestion control—Backpressure technique, Choke packet technique, Implicit congestion signaling and Explicit congestion signaling. There are three major congestion control issues—Fairness, Quality of Service (QoS) and Reservation scheme.

Congestion management (CM) scheme for SGs through DR in [130], optimizes two objectives—acceptable congestion and congestion cost; including DR by choosing optimal mix of generation rescheduling and DR of participating buses by minimizing the impact on revenues and customer satisfaction using Ant Colony Optimization and fuzzy technique to choose the best compromise solution from the set of Pareto optimal solutions. In [131], a novel congestion management mechanism for a WiMAX based system to manage various in-band interferences using Periodical Sensing (PS) to obtain the real time interference information and to define cross layer message between PHY and MAC to deliver the interference information to downlink and uplink, respectively. Design of spread spectrum schemes to achieve *feasible* communication under jamming attacks and minimization of message delay for *timely* communication in power applications have been addressed

for the SG by wireless networks. In [132], it is shown that the worst-case message delay is a U-shaped function of network traffic load, which interestingly indicates that, increasing redundant traffic (*camouflage*) can improve the worst-case delay performance. To overcome the limitations of earlier works on mobile agents, such as load, lack of memory space and improper communication with clients, in [133], MAS has been proposed which interconnects separately developed mobile agents, thus achieving load balancing and reduction in delay in propagation time, using web logic server (J2EE). Considering the on-line monitoring and controlling abilities of a SG, [134] addressed reconfiguration as an effective methodology to solve the distribution network congestion problem that might be due to a large amount of simultaneous energy generation from microDGs. Genetic algorithm is used to determine the optimal configuration.

Ref. [135] presents a concept wherein each consumer is under the jurisdiction of exactly one Balancing Responsible Party (BRP), who buys energy at a day-ahead electricity market on behalf of the consumer, considering distribution grid interconnecting a number of consumers with flexible power consumption. BRPs can utilize the flexibility of the consumers to minimize the imbalance between the consumed and the purchased energy, thereby avoiding trading balancing energy at unfavorable prices. SCUC proposed in [136] to identify annual congestion in large scale grid, tested on the WECC grid and the results obtained from the test were mapped on GIS, to visually locate the congested transmission lines in WECC. By linking the transmission congestion information with other cost information in WECC, the approach allows for viewing the price of electricity at various WECC locations. Analysis of key stakeholders in [137], mainly grid congestion problem, several conceptualized solution approaches and key operations have been presented along with three potential strategies for congestion management. Distributed load management in SG infrastructures presented in [138], to control power demand at peak hours, by means of dynamic pricing strategies, wherein, the proposed distributed solution is based on a network congestion game, to converge in a finite number of steps to a pure Nash equilibrium solution. Comparison of throughput in ideal and real performance situations is shown in Fig. 3.1, that could be referred as important guiding factor for effective smart grid design.

3.5. *Energy efficiency [139–158]*

In general, energy efficiency means using less energy to produce the same amount of the useful output. Increasing energy prices and the greenhouse effect lead to more awareness of energy efficiency of electricity supply. Recent developments in this domain include next to large scale technologies such as wind turbine parks. Such domestic technologies can be divided into distributed generation, energy storage and demand side load management. Control algorithms optimizing a combination of these techniques could raise the energy reduction potential of the individual techniques.

Refs. [139,140] review concepts and research works carried out on optimizing the energy efficiency and SG, expressing need to have a tool capable of simulating the various technologies and applications of SG to make it possible to predict the results of the energy management systems in the consumer loads, as well as for legislative and regulatory changes for creation of a favorable environment for implementation of SG technologies. Three-step optimization methodology has been presented in [141], using offline local prediction, offline global planning and online local scheduling validated by simulations and field tests. Methodology, procedures, metrics, and tools to comprehensively evaluate the main benefits, in terms of energy efficiency and savings, as well as performance of an ICT platform have been discussed in [142]. Cost-aware Smart Microgrid Network (CoSMoNet) in [143], for economic power transactions within the SMGN, is based on an Integer Linear Programming (ILP) formulation to match excess energy in storage banks of a group of SMGs to the demands of other SMGs whose load cannot be accommodated by their local supply. Generic management methodology in [144], applicable for most domestic technologies, scenarios and optimization objectives, applied to both local scale optimization objectives (a single house) and global scale optimization objectives (multiple houses) and simulated to reach both local and global objectives. Post literature survey, considering transition from legacy conventional electric grid to SG as challenge in [145], identified high power electronics as key technology to support energy efficiency, renewables' integration and SG, supported by techno-commercial data. Three-step control methodology in [146], to manage cooperation between various technologies, focused on domestic energy streams, achieves (global) objectives like peak shaving or forming a virtual power plant without harming comfort of residents. WSN-Based residential Energy Management Scheme in [147], wirelessly connects non-urgent appliances to the smart meter to respond to resident's command with economical suggestion, and help them shift their non-urgent appliances to the off-peak hours to alleviate high peak load, reduce green-house gas emission, optimal generation plan to satisfy resident demands and reduction in total utility cost. An improved simulator is presented in [148], to model (domestic) energy usage and to analyze control strategies and improved technology on the system as a whole. Increasing energy prices and the greenhouse effect lead to more awareness of energy

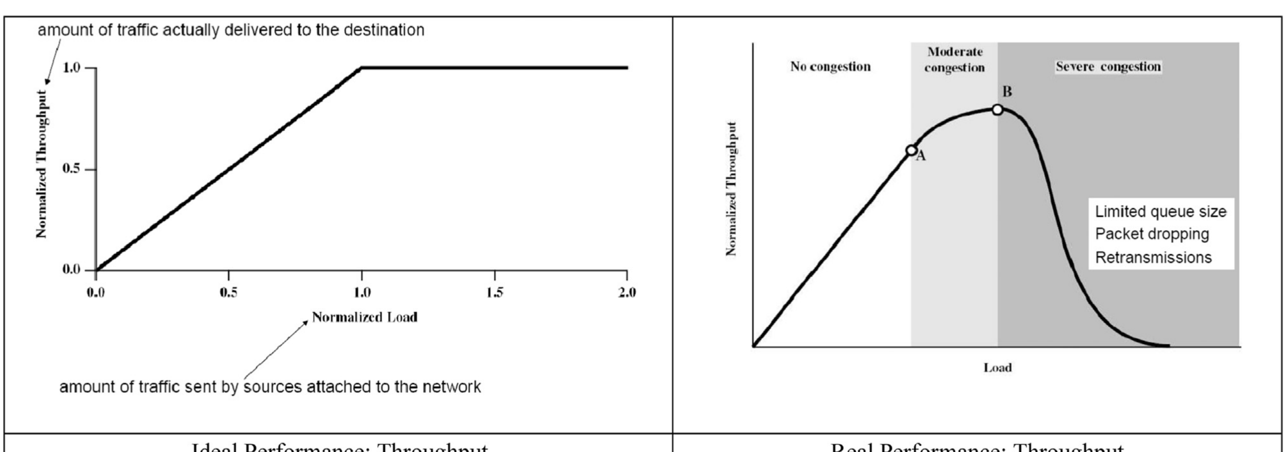

Fig. 3.1. Comparison of throughput in ideal and real performance situations for smart grid congestion [129].

efficiency of electricity supply. As extension of [148], in [149], Model Predictive Control (MPC) has been added to incorporate future states in the control with ability to work around prediction errors and improves the irregular behavior of devices, resulting in more stable situations, wherein operators can opportunistically leverage the delay tolerance of energy demands in order to balance the energy load over time, reduce total operational cost and enhance energy efficiency. Impact of malicious cyber-attacks on the energy efficiency of the grid has been studied in [150], using a simplified setup, wherein the energy demands of the SG consumers are intercepted and altered by an active attacker before they arrive at the operator with limited intrusion detection capabilities. To address the need to take action in near real time during malfunctioning in SG, for reallocating the power to minimize the disruption, in [151], the authors present a collection of ILP models designed to identify optimal combinations of supply sources, demand sites for them to serve, and the pathways along which the reallocated power should flow, with alternative sources such as wind power. A simulator configured with multiple intelligent distributed software agents has been developed to support the evaluation of the model solutions. Performance of EMS and BAS in smart environment using WSN has been evaluated in [152]. Model selected has been implemented in real environment using WSN on testbed to analyze feasibiilty of WSN application. The authors claimed to save up to 57% in energy cost, with enhancement in overall energy efficiency. An approach to construct abstracted scans of sensor network health in [153], by applying in-network aggregation of network states. A residual energy scan and simulations show that the proposed approach has good scalability and energy-efficiency characteristics. In [154], a model is defined and a developed simulator is described to analyse the impact of different combinations of micro-generators, energy buffers, appliances and control algorithms on the energy efficiency, both within the house and on larger scale. Smart wireless DC micro-grid suitable for efficient utilization of energy available from DREGs has been described in [155], with experimental demo using a 40 kw solar PV array delivering power to fluorescent lighting; other DC loads such as LEDs and DC ceiling fans. First-order calculations have been presented to show significant energy savings. Ref. [156] outlines in a nutshell the concept and characteristics of SG with generation, transmission and distribution. Appliance Coordination with Feed In (ACORD-FI) scheme in [157], for energy-aware smart homes significantly decreases the cost of energy consumption of home appliances, enhancing energy efficiency. Performance of iHEM and OREM are compared in [158] to minimize energy expenses of the consumers, reduce the carbon emissions, with iHEM being more flexible due to WSHAN.

3.6. *Latency [159–173]*

Due to tight coupling between consumer-side and SG equipments like substation transformers, capacitors, relays, etc., any fault anywhere or incident responsible for power quality degradation in distribution actuates time-bound load control actions in energy-efficient buildings. Hence, real-time asset monitoring be mandatory and communication plays a major role to allow services such as self-healing, real-time demand response and efficient use of energy. For tight integration of renewables, due to the large quantity, distributed locations and intermittent nature of energy resources (such as wind and solar), SG largely depends upon communication for rapid balancing between demand and supply. Fast, efficient and accurate demand-supply matching yields economic and technical benefits. Plants with high running costs (e.g. gas turbine power stations) could be avoided during peak hours to significantly improve grid stability–reliability. All the afore-mentioned specifications translates into requirements of time-bound response of grid equipments, hence latency (maximum technically permissible-tolerable time delay) be extremely crucial as it directly affects Quality of Service (QoS) performance. Transmitting delay-critical data from SG assets to the controller base station may require data prioritization and delay-responsiveness in condition monitoring applications.

Delay-responsive, cross layer scheme with linear backoff (LDRX) mechanism in [159] to address delay and service requirements of the SG monitoring applications, which has been designed to operate in cluster-tree WSN topology suitable for monitoring wide areas such as electrical substations or large installations. Medium access scheme, namely delay-responsive, cross layer (DRX) data transmission in [160], to address delay and service differentiation requirements of the SG, is based on delay-estimation and data prioritization procedures. A comprehensive performance evaluation of this scheme has been provided with necessary tradeoffs. Post study of the influence of some inherent properties of data communication networks (e.g. packet loss and latency) in [161], on the performance of the balance between electricity supply and demand, models for demand and different power plants have been simulated. Review of the work in [162], related for guaranteeing availability in SG communications has been split into three categories: defences against attacks, guarantee of critical realtime systems, and extension of communications availability and their respective latency requirements have been outlined. To increase availability of communications in SG, network architecture using cognitive radio technologies has also been proposed. Ref. [163] proposes an Energy Sorting Protocol (ESP) architecture which employs clustering for wireless micro-sensor networks for low energy dissipation and latency without sacrificing application specific quality. Cluster formation algorithm proposed and simulated minimization of energy and latency, eventually minimizing protocol overhead. Method to simulate, design and test the adequacy of a high-bandwidth, networked communication system in [164] supports phasor measurements on the high voltage power grid transmission system. Communication design, simulation and testing have been formulated from the viewpoint of the anticipated power applications. Design, simulation and evaluation of ZigBee WSNs for condition monitoring of delay sensitive data in wind turbines (renewable energy sources) presented in [165] with an approach to reduce the end-to-end delay and to provide service differentiation for sensor nodes that are transmitting delay sensitive data by modifying the existing IEEE 802.15.4 MAC protocol to help optimizing the SG operation for near real-time asset monitoring and enhance demand response. Cross layer scheme proposed in [166], is fairness-aware and delay-aware. Fairness in delay-aware cross layer data transmission scheme (FDRX) is based on delay-estimation and data prioritization steps, performed prior to data transmission by the application layer. The proposed scheme is able to reduce end-to-end delay for data demanding timely delivery. Performance of two WSN based monitoring schemes in [167], namely the delay-responsive, cross layer (DRX) data transmission scheme, and the fair and delay-aware cross layer (FDRX) data transmission scheme in various SG environments have been evaluated. Considering an outdoor substation, an underground transformer vault and an indoor power room, it has been shown that DRX has lower end-to-end delay than FDRX, delivery ratio of both DRX and FDRX degrades in the outdoor substation as compared to underground transformer vault and both are able to satisfy the tight delay requirements of the SG. The goal of [168] is to model the communication latency among distributed intelligent agents, considering it an inherent parameter that affects the performance of the communication network—the backbone of the multi-agent system. Two abnormal events occurring in the modified IEEE 34 node test feeder have been simulated to validate the proposed

methodology. To meet the requirements of cognitive wireless networks in SG communications, in [169], the technical challenges and the solutions of cognitive radio networking with multimedia applications for SG communication infrastructures have been evaluated and a guideline for future SG multimedia communication infrastructure design has been presented. Addition of QoS has been proposed in [170] into low cost protocols by providing differentiated service for traffic of different priority at the MAC layer and using ZigBee as an example, employing analytical delay model and simulation results. Viability of PLC for SG communication has been assessed in [171] by categorizing the SG data traffic into two general traffic classes – home area network data traffic and distribution automation data traffic. Later, simulated using network simulator-2 for SG realization and for some future SG advanced applications, latency and reliability have been identified as the main SG communication network requirements.

3.7. Security [172–192]

The SG significantly enhances the efficiency of energy consumption, by utilizing bidirectional communication between consumers and utility operators, wherein, operators opportunistically leverage the delay tolerance of energy demands to balance the energy load over time, hence, reducing total operational cost. Such an opportunity also welcomes security threats as the grid becomes more vulnerable to cyber-attacks. Hence, the next generation electrical grids shall need to rely heavily on a complex network of computers, software, and communication technologies in order to encounter 24×7 security threats. Advanced-intelligent sensors smart metering, and the integration of distributed generation resources, urge to keep more and more data online, etc. are likely to open higher probabilities of security threats. Therefore, even for customer-centric critical SG applications like AMI, DR, etc. and dealing in financial terms for billing information, data privacy of customers has been emerging as the major challenge. Furthermore, wireless communication provide many benefits such as low cost, quick-adhoc-nomadic deployability, high speed links, simple configuration, etc. but, they are observed more vulnerable to security attacks than wired ones. Hence, development of appropriate wireless communication architecture and its security measures have been extremely important for SG.

AMI systems architecture and data movements have been analyzed in [172], specifically with reference to information leaks. A theoretical network architecture, model to minimize attack vectors, secured data location DBPC (Data Base Processing Center) instead of traditional DBMS (Data Base Management System) have been discussed. Systematical reliability and security assessment process for the electric power communication network could be studied in [173]. Three-level hierarchical architecture and an application system have been developed for assessment of reliability and security. SG security key standards NIST inter agency report 7628, IEC 61850 & GB/T22239 security classified protection standards, IEC 62351 on SG security, ISO/IEC 15408 & GB18336 security assessment standards and ISO 27001 & GB/T22080 information security management standards have been summerized in [174] along with security technology and corresponding standards. Conceptual design for an application of wireless sensor technology has been presented in [175] for assessment of structural health of transmission lines and their implementation to improve the observability and reliability of power systems. A two-layer sensor network model has been presented for overcoming the communication range limitations of smart sensors, and two operational modes for enhanced energy efficiency have been introduced validated by simulation. Communication security aspect has been focused in [176], which deals with the distribution component of the SG. Consequently, the AMI network security infrastructure coupled with the data communication toward the transmission infrastructure has also been targeted with aims to remidiate correlated vulnerabilities in these systems and mitigate the associated risks for enhancing cyber security of grid. A new utility computer network security management and authentication for actions/commands requests in SG operations have been proposed in [177], to cover multiple security domains in a new security architecture with strategy and procedure of security checks and authentications of commands requests for operations in the host AEPS with case studies. Multi-level framework for a trust model presented in [178] aims at development of High Assurance Smart Grid (HASG) model to support a distributed-hierarchical control system architecture and suggests that systems be designed in ways to narrow the sphere of implied trust by expecting the compromise of adjacent systems, thereby reducing the sphere of vulnerability. Communication framework to classify and integrate networking entities in a SG environment have been presented in [179] along with communication technologies and protocols and security considerations. [180] explains the connections between grid operational procedures and cyber attacks. First, with an example illustrates how data integrity attacks can cause economic and physical damage by misleading operators into taking inappropriate decisions, later, unobservable data integrity attacks involving power meter data has been explained. Metrics have been developed to assess the economic impact of these attacks and they could be used to prioritize the adoption of appropriate countermeasures. DNP3 based Network cyber-security architecture for SG in [181] is focused to provide cyber-security for smart load management devices that are networked for collaborative operations and accessible by utility staff and consumers. DNP3 is utilized to produce protocols disjoints between DNP3 devices for strictly regulated power system operations and TCP/IP devices for smart load management accessible by utility consumers to limit effectiveness of attacks from consumer TCP/IP devices. Preliminary results of a research activity aimed at quantitatively evaluating the impact from different standpoints including memory consumption, network performance, and energy consumption in [182] exploits a free implementation of the IEEE 802.15.4 security sublayer. Ref. [150] investigates the impact of malicious cyber-attacks on the energy efficiency of the grid in a simplified setup, where in a simple model, energy demands are intercepted and altered by an active attacker before they arrive at the operator (with limited intrusion detection capabilities). Then, the results of optimization problem solution shows that, as opposed to facilitating cost reduction in the SG, increasing the delay tolerance of the energy demands potentially allowed the attacker to force increased costs on the system. Security issues including attack and attacker, and security principles, specifically when WSNs have been deployed in insecured environment, are inluded in [183] along with layering based attacks for physical layer, data link layer, network layer and transport layer, along with a discussion on cryptography. Hardware architecture of the security processing for ZigBee has been presented in [184], which satisfies the constraints IEEE 802.15.4 standard requirements, mainly consist of the critical response time, the verification delay, and the throughput, along with security processing with considerable low power consumption. In [185], security threats on SG communication networks have been classified and evaluated. Then, using top-down analysis, goals of potential attacks have been categorized into three types: network availability, data integrity and information privacy. Then qualitative analysis of both the impact and feasibility of all the three types of attacks have been presented with security objectives, experimental validations for quantitative evaluation and the impact of Denial-of-Service (DoS) attacks. Ref. [186] assumes a smart home with a wireless sensor network based on ZigBee. The earlier approach of authors that used web services to remotely

interact with smart home elements in a SG environment has been extended by including quality of service, security and XMPP (eXtensible Messaging and Presence Protocol). Different levels of access control and advantages of XMPP to provide near real-time communication and security and secured web services to facilitate selling of energy back to the grid have been included. To review matters of SG security and to examine the effect of hacker attacks on SG network parameters – are the dual objectives. Development of appropriate wireless communication architecture and its security measures have been considered as two problems investigated in [187]. Firstly, a wireless communication architecture has been proposed for a SDG based on WMNs to analyze security framework, and then within that framework, a new intrusion detection and response scheme, called smart tracking firewall, has been developed to meet the special requirements, validated by performance results. Ref. [188] initially analyzed and discussed the characters of SG, then abstracted hierarchical information and communication model, based on which, the information security risks and information security protection demands of SG have been studied and summarized. Different SG and common information and cyber security standards and guidelines have been surveyed and compared. Post discussing applications of sensor networks in electric power systems in [189], characteristics of SG WSNs have been summarized including threats and security requirements. Based on the same, reference security architecture to guide the design of the security solutions of WSNs in SG systems has been presented. In [190], the design method of information security protection architecture, requirements and security risks involved have been analyzed for US and China SGs. An information security protection model, overall information security protection strategy and requirements have been proposed considering the characteristics of China SG. Based on this model, the information security protection framework has been designed to support the SG. Common security issues in SG standards have been investigated in [191] that employ communication protocols and the common causes for such issues. Security considerations have been proposed; to address them, guidelines for drafting security into SG standards have been presented, either during updation or during new standards developments. Examples on ZigBee Smart Energy Profile (SEP) standard have been included. As reported in [192], due to the shared nature of the wireless medium, inspite of being the best, ZigBee deployments may face security challenges and interference issues, which must be addressed, considering the interests of both utility and consumer, the authors of [192] have taken a comprehensive look at wireless security in the AMI based home-area network by identifying a wide range of possible vulnerabilities and suggested necessary countermeasures.

4. Conclusions

The paper is an outcome of study, survey and presentation of smart grid from the viewpoint of an Instrumentation Engineer. The paper presents interesting analogy of 'Smart Grid Communication System' to 'Instrumentation Telemetry'. Initially, beginning with introductory concepts including basic building blocks of smart grid and architectural information, later the paper converges over its focused area—smart Grid critical applications and parameters. Total 6 critical applications and 7 critical parameters have been identified that affect smart grid design and performance. For each critical application or parameter, the conceptual understanding has been included initially and later results of literature review of relevant recent works have been included. Research works describing novel approaches, methodologies, pilot designs, test beds, validation approaches and standardization have been preferred. The paper describes interesting relationship of Critical Applications and Parameters on overall design and performance as well as draws reader's attention toward most recent technological research works in each segment and hence could serve as base to support future works in diversified directions for smart grid research.

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